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TITLE		
Effect of Ground Plane Protrusions on the Sixty-Cycle and Impulse Flashover Mechanism of Bushings.		
ABSTRACT		

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Title Page

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TITLE Effect of Ground Plane Protrusions on the Sixty-Cycle and Impulse Flashover Mechanism of Bushings.		
ABSTRACT The qualitative explanation of the bushing flashover mechanisms is given. The effect of ground plane protrusions on the flashover mechanisms of the bushings was investigated for positive and negative polarity impulse and sixty-cycle voltages.		
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CONCLUSIONS 1. The presence of a ground rod had no appreciable effect on positive polarity impulse corona starting or flashover voltages. 2. The presence of a ground rod appreciably lowers the negative polarity impulse corona starting and flashover voltages. 3. The presence of a ground rod lowers both the sixty-cycle corona starting and flashover values. A space charge condition surrounding the ground rod minimizes its effect on the bushing flashover voltage.		

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EFFECT OF GROUND PLANE PROTRUSIONS ON THE SIXTY-CYCLE AND IMPULSE FLASHOVER
MECHANISM OF BUSHINGS.

INTRODUCTION:

This investigation was undertaken to determine the mechanism of bushing flashover and how it is affected by ground plane configuration. The mechanism of streamer formation of long sparks has been well established and can be found in great detail in the book, "The Mechanism of the Electric Spark" by L.B. Loeb and J.M. Meek (Stanford Press, 1941). Specifically, the breakdown mechanism of non-uniform field gaps under impulse and sixty-cycle voltage conditions are treated in TIS reports 50TP1818 and 52TP26.

SUMMARY:

Bushing flashover is initiated by either one or both of two flashover mechanisms depending on type of voltage applied, bushing size and the dome and ground plane configurations. These two flashover mechanisms, the mechanism of positive streamer formation from the anode and the mechanism of avalanche-retrograde-streamer formation from the cathode, are briefly described in this report.

With a flat ground plane, it was found that the flashover was initiated at the bushing dome in all cases. With impulse voltage applied, the mechanism initiating flashover depended on the polarity of voltage applied. With negative polarity impulse, the avalanche-retrograde-streamer formation from the cathode was the initiating mechanism and with positive polarity voltage applied, positive streamer formation was the initiating mechanism. With sixty-cycle voltage applied the initiating mechanism depended on the shape of the bushing dome as well as the bushing size. It was found that the flashover was initiated by the positive streamer formation when the 138 KV bushing was tested. For the 73 KV type OF bushing, flashover could be initiated by either mechanism but was mostly that of positive streamer formation.

With a ground rod protrusion on the ground plane, the flashover mechanism involved depends on the polarity of voltage applied and the ground rod length. For positive polarity impulse applied to the bushing, the ground rod had practically no effect on the flashover values and the flashover mechanism involved was that of positive streamer formation from the anode (bushing dome). With negative polarity impulse applied, the ground rod markedly lowered the flashover values of the bushing. In this case, the bushing flashover was initiated from the anode (ground rod) by positive streamer mechanism. For sixty-cycle voltage applied, a slight lowering of the flashover values was noted when the ground rod was present. Flashover was initiated at the ground rod when it was positive by the positive streamer mechanism.

It was found that under sixty-cycle voltage conditions, the effect of the ground rod on the flashover voltage was not nearly as large as for negative polarity impulse. This is explained on the basis of a negative ion space charge formed during the negative half-cycle of the applied sixty-cycle voltage and surrounding the ground rod tip.

Further tests showing the effect of the bushing dome configuration on the flashover mechanism for positive and negative polarity impulse and sixty-cycle voltages are reported in 52TP20. The dome configuration in this report was determined by the presence and location of a sharp lip on the bushing dome.

EQUIPMENT AND METHOD OF TEST:

Two bushings were used in these tests, a 138 KV type F bushing and a 73 KV type OF bushing. The bushing test set up was arranged as follows: the bushing to be tested was supported on a flat ground plane so that the bottom porcelain of the bushing extended into a tank and was completely covered with oil. The ground plane diameter was 5' for a 73 KV bushing and a 6' x 8' oval for the 138 KV bushing. When the ground rod was used, it was supported on the tank top 6" away from the bushing porcelain. The ground rod length used for these tests extended 2" for the 73 KV bushing and 6", 10", 14" and 16" for the 138 KV bushing above the uppermost ground metal of the bushing.

Sixty-cycle, positive and negative polarity impulse flashover tests were made on each bushing, both with and without the ground rods present. In all cases, corona measurements coupled with visual observation and photographs of corona were made.

For the sixty-cycle tests, the voltage was applied at a rate of approximately 3 KV/sec. to flashover. The flashover polarity and corona measurements were made by the HC-10 oscillograph described in report 50TP77.

For the impulse tests, a 1-1/2 x 40 μ s voltage wave was used for both the positive and negative impulse tests. The voltage was first applied several levels below the corona starting voltage with three impulses per level and increased in 30 KV levels for the 73 KV bushing and 50 KV levels for the 138 KV bushings up to flashover. After obtaining one flashover at the minimum flashover voltage level, the voltage was then reduced and the same procedure was followed to obtain the next and all subsequent flashovers. After the completion of two or more tests, all flashover voltage levels were averaged together resulting in a value termed the average impulse flashover voltage. This term is used throughout the report denoting the impulse voltage as described above. Corona detection as described in report 49TP6 was carried out during the impulse tests.

DISCUSSION OF THE BREAKDOWN MECHANISM FOR LONG SPARKS:

In unsymmetrical and otherwise non-uniform field gaps where a large gap spacing is encountered, Townsend's theory of spark breakdown no longer holds true and the streamer theory of spark discharge is necessary to explain the

breakdown mechanism. Since the bushing flashover takes place across an unsymmetrical non-uniform field gap, the streamer theory of spark discharge must also apply for this case. A complete discussion of the streamer mechanisms involved is presented in Loeb's and Meek's book⁽¹⁾. In brief, the mechanism of streamer formation and flashover is as follows.

Mechanism of Positive Streamer Formation.

When the field strength (E_F) in the vicinity of the anode becomes sufficiently high while that in the vicinity of cathode or ground plane remains low, the breakdown mechanism will proceed as follows.

Free electrons near the anode will be drawn toward this electrode, being accelerated as they approach the region of higher field strength, forming an electron avalanche as they travel. A great number of positive ions will be left in the path of the rapidly moving electron avalanche. These positive ions, due to their low mobilities will remain relatively stationary and constitute a positive ion space charge having a field intensity of (E_S). This field (E_S) will be additive with the applied field (E_F) resulting in a greatly enhanced field on the cathode side of the space charge. Accompanying the cumulative ionization of the electron avalanche, there is produced by the electrons some four to ten times as many excited atoms or molecules as ions. These excited atoms or molecules emit radiation of very short wave lengths in some 10^{-8} seconds. These radiations, or photons as they are called, are highly absorbed by the air and cause the formation of new photo electrons. The new photo-electrons created in the enhanced field of the positive ion space charge described above will be drawn rapidly toward this space charge and form a photo-electron avalanche as they advance toward it. These electrons will be drawn into the positive ion space charge making it a conducting plasma all the way to the anode. The positive ions left behind by each successive photo-electron avalanche will extend the space charge toward the cathode while the photons created by the electron avalanche will create new electrons and so continue the process across the gap to the cathode. In this fashion, the positive ion space charge develops toward the cathode as a self propagating positive space charge streamer.

As the streamer approaches the cathode, photons will produce intense ionization very near the cathode resulting in positive ions bombardment of it to increase its secondary emission and begin to form a cathode spot which produces a rush of electrons into the streamer. These electrons will pass up the ionized channel multiplying the electrons present by a large factor. The channel is thus rendered highly conducting and if the metal can emit a copious supply of electrons, the flow of the electrons continues up the channel, increasing its conductivity and forming a spark.

The Mechanism of Avalanche-Retrograde-Streamer Formation.

Where the breakdown of the gap is initiated at the cathode, the mechanism involved is essentially that of electron avalanche formation combined with streamer action in a manner that is quite different from that of the positive streamer formation.

(1) "The Mechanism of the Electric Spark", L.B. Loeb and J.M. Meek, Stanford University Press, 1941.

The mechanism for cathode initiated breakdown proceeds as follows.

When the field strength (E_f) in the vicinity of the cathode becomes sufficiently high, the electrons near the cathode will be repelled forming an electron avalanche as they travel away from the region of highest field intensity. Before the electron avalanche is well advanced, two factors tend to retard it. First, as the electron avalanche travels away from the cathode, the diverging field becomes less effective in aiding the avalanche propagation; second, the field of the positive ion space charge left in the avalanche trail will also have a retarding action on the advance of the electron cloud. Under these conditions, the avalanche is only allowed to propagate a distance X_1 . At this time, a streamer will propagate in the retrograde direction from the positive ion space charge back to the cathode. Once the streamer tip reaches the cathode and the supply of electrons run up the channel, making it a conducting filament of plasma, the negative electrode will have extended itself a distance X_1 in the gap. Meanwhile, the avalanche will again proceed at its normal velocity until it reaches a distance of $X_1 + X_2$ from the cathode where again the positive ion space charge field is sufficiently great to retard the advance of the electron cloud, and a new streamer advances toward the cathode from $X_1 + X_2$ to join the filament of plasma with its tip at X_1 . This process continues until the avalanche approaches the anode, when, as in the case in an overvolted gap, a positive streamer from the anode finally closes the gap, giving rise to breakdown.

The breakdown process is thus seen to be essentially avalanche advance combined with streamer action.

Further Consideration of the Breakdown Mechanism.

In many cases where an unsymmetrical or non-uniform field gap is under consideration, the fields at one or both electrodes may be very high, while those in mid-gap are low, in fact, so low that Townsend's ionization coefficient α has a value of zero in these regions. In such cases, while it is still correct to infer that the streamer process carries with itself considerable field distortion and thus extends the electrode field or fields out into the gap, it is likely that the mid-gap fields are so low that even with the streamer field distortion, further streamer propagation is prohibited. Thus, only local or partial breakdown in the form of corona discharges from one or both electrodes will occur. This type discharge was observed prior to flashover of the bushings used in the tests for this report.

For large electrodes, where a high field strength extends out into the gap, both the positive streamer and the avalanche-retrograde-streamer mechanism can materialize at nearly the same voltage. The propagation or advance of these streamers at the same field strength, once they are initiated, become quite different. The positive streamer carries with it the high field gradient from the electrode surface and will advance easily as was shown in the discussion of this mechanism. On the otherhand, the avalanche-retrograde-streamer mechanism proceeds outward where the electrons at the avalanche tip find themselves in a weak field region which is farther attenuated by the positive ion space charge of the avalanche and the avalanche advance will be retarded. The field between the

positive ion space charge and the cathode is increased while the weak declining field ahead of the electron avalanche to the anode is not enhanced in equal measure. Hence, the avalanche-retrograde-streamer mechanism, while it can be initiated at nearly the same voltage as the positive streamer, will not readily advance across the gap. Therefore, breakdown by the retrograde-streamer mechanism will take place at higher electrode potentials and less readily at lower potentials than will those by the positive streamer mechanism.

In such gaps where the breakdown is initiated by the retrograde-streamer mechanism, it is very doubtful that breakdown can be completed by this process alone owing to the low mid-gap field values. There is evidence⁽²⁾ to show that breakdown started by the retrograde streamer process is usually completed by a positive streamer from the anode meeting the streamer from the cathode at some mid-gap position.

RESULTS AND DISCUSSION:

A. Positive Polarity Impulse Flashover. Tables 1 and 2.

Observations: 73 KV Type OF Bushing.

(1) Flat ground plane.

- (a) Average corona starting voltage - 365 KV.
- (b) Average flashover voltage - 435 KV.
- (c) Corona was observed only on the bushing dome.

(2) 2" rod on the ground plane.

- (a) Average corona starting voltage - 345 KV.
- (b) Average flashover voltage - 425 KV.
- (c) Corona was observed on the bushing dome prior to flashover.
- (d) Only one out of four flashovers took place between the bushing dome and the 2" ground rod. The other three were between the dome and various places on the ground plane.

Observations: 138 KV type F bushing.

(1) Flat ground plane.

- (a) Average corona starting voltage - 800 KV.
- (b) Average flashover voltage - 866 KV.
- (c) Corona was observed on the bushing dome prior to flashover.
- (d) The corona observed was of the streamer type shown on PL-34721.

(2) "Proc. Roy. Soc." E.E. Allibone and J.M. Meek, (London) A,166,97 - 1938.

(2) 6" rod on the ground plane.

- (a) Average corona starting voltage - 850 KV.
- (b) Average flashover voltage - 875 KV.
- (c) Corona was observed on the bushing dome prior to flashover.
- (d) All flashovers took place between the bushing dome and the 6" ground rod.

(3) 10" rod on the ground plane.

- (a) Average corona starting voltage - 800 KV.
- (b) Average flashover voltage - 850 KV.
- (c) Corona was observed on the bushing dome prior to flashover. The type of corona observed is shown on PL-34722.
- (d) All flashovers took place between the bushing dome and the 10" ground rod.

Discussion.

From the above observations and the flashover data of Tables 1 and 2, the following conclusions can be drawn:

- 1) The presence of a ground rod does not appreciably effect the positive polarity impulse flashover value.
- 2) The presence of a ground rod does not appreciably effect the corona starting values. In all cases, corona occurred only on the bushing dome prior to flashover.
- 3) The flashover path for the 73 KV type OF bushing was independent of the position of the 2" ground rod while for the 138 KV type F bushing, flashover usually took place between the ground rod and the bushing dome. Apparently, the longer ground rods, 6" and 10", have some influence on the positive polarity flashover as indicated by the fact that the flashover took place between them and the bushing dome. However, this effect must be small as it does not show up in either corona starting or average flashover values.

From the observations and conclusions, it becomes evident that the positive polarity flashover is initiated from the bushing dome and is quite independent of the ground plane configuration. This is further illustrated by the corona streamer formation on photograph PL-34721. The corona streamer can be seen extending out from the dome for 6" or 8". It was also observed that the arc path for positive polarity tended to bow outward rather than hug the bushing during flashover. This would be the logical direction the arc path should take, providing the positive streamer mechanism initiated breakdown, as the anode extends all the way down the bushing and the positive streamer tends to go in a direction away from it.

The logical conclusion is that, since the bushing dome is the anode when positive polarity voltage is applied, flashover takes place by means of the positive streamer mechanism from the anode as described earlier in this report.

B. Negative Polarity Impulse Flashover. Tables 3 and 4.

Observations: 73 KV type OF bushing.

(1) Flat ground plane.

- (a) Average corona starting voltage - 365 KV.
- (b) Average flashover voltage - 477 KV.
- (c) Corona was observed only on the bushing dome.

(2) 2" rod on the ground plane.

- (a) Average corona starting voltage - 335 KV.
- (b) Average flashover voltage - 385 KV.
- (c) All flashover paths were between the ground rod and bushing dome.
- (d) Corona was observed to start from the ground rod. At breakdown level, it was not unusual to have corona both on the dome and on the ground rod.

Observations: 138 KV type F bushing.

(1) Flat ground plane.

- (a) Average corona starting voltage - 750 KV.
- (b) Average flashover voltage - 900 KV.
- (c) Corona was observed only on the bushing dome prior to flashover.
- (d) PL-34723 shows the negative polarity impulse corona on the bushing dome.

(2) 6" rod on the ground plane.

- (a) Average corona starting voltage - 550 KV.
- (b) Average flashover voltage - 650 KV.
- (c) Corona was observed on the ground rod prior to breakdown.
- (d) All flashover paths were between the ground rod and bushing dome.
- (e) PL-34724 shows the corona extending up the bushing from the ground rod.

(3) 10" rod on the ground plane.

- (a) Average corona starting voltage - 400 KV.
- (b) Average flashover voltage - 550 KV.

- (c) Corona was observed on the ground rod prior to breakdown similar to that shown in PL-34724.
- (d) All flashover paths were between the bushing dome and the ground rod.

Discussion:

From the above observations and the flashover data of Tables 3 and 4, the following conclusions can be drawn:

- 1) The presence of a ground rod appreciably lowers the negative polarity impulse flashover values.
- 2) Corona starting voltages were appreciably lowered when the ground rod was present. This was especially pronounced with the 138 KV bushing. When no ground rod was present in this case, corona was observed only on the bushing dome and at a voltage that was higher than the flashover voltage when the 6" and 10" ground rods were present.
- 3) The flashover path always occurred between the ground rod and bushing dome when the ground rod was present. The arc path, in this case, always tended to hug the bushing surface. This is just the opposite to that observed for the positive polarity impulse flashover. When no ground rod was present, the arc path tended to bow away from the bushing as it did for positive polarity.

From the above observations and conclusions, it seems evident that flashover is initiated by two different streamer mechanisms, depending on whether or not a ground rod is present.

For the first case, where no ground rod is present, flashover takes place at a high voltage, corona occurs only on the bushing dome prior to flashover as shown on PL-34723 and the breakdown path tends to bow out away from the bushing. These facts lead one to believe that the flashover mechanism is initiated at the cathode or the bushing dome for this case where negative polarity impulse is applied. If this is true, then the mechanism involved in the bushing flashover must be that of the avalanche-retrograde-streamer formation. It is quite unlikely, however, that this mechanism alone causes the flashover. As was stated previously, once the retrograde streamer spans a portion of the gap, the remainder of the gap is in an over-volted condition and is quite possible for a positive streamer to start from the anode (the ground plane in this case) and meet the retrograde streamer some where in the mid-gap completing the breakdown process.

For the second case, where the ground rod is present, the flashover voltage for the 138 KV bushing is lowered to a value less than the corona starting voltage with no ground rod present. For the 73 KV bushing, the flashover voltage is lowered to a value that is only slightly higher than the corona starting voltage when no ground rod is present. In both cases, a lowering of corona starting voltage was found. Corona was only on the ground rod prior to flashover for the

138 KV bushing as shown by PL-34724. For the 73 KV bushing, corona was observed on both the ground rod and the bushing dome prior to breakdown. In all cases, the arc path tended to hug the bushing surface.

It was previously shown for positive polarity impulse that, when the flashover was initiated at the bushing dome the ground rod had no influence on either corona or flashover values. In this case, however, the ground rod markedly influences both the corona and flashover values. These observations and test results indicate that the flashover is a ground rod initiated mechanism. This being so, then the mechanism involved is that of positive streamer formation from the ground rod (anode). It is not too unlikely, that for the 73 KV bushing with the 2" ground rod, the positive streamer formation from the anode (ground rod) and avalanche-retrograde-streamer formation from the cathode (bushing dome) are both involved in the flashover mechanism, but it seems evident from the results of this study that the positive streamer mechanisms from the anode (ground rod) plays the predominant role.

C. Sixty-Cycle Flashover. Table 5.

Observations: 73 KV type OF bushing, Cat. 2595905G1.

(1) Flat ground plane.

- (a) Average flashover voltage - 251 KV (RMS).
- (b) For 8 flashover tests, 5 occurred during the positive half-cycle of applied voltage and 3 during the negative.
- (c) In general, the corona during the positive half-cycle of the applied voltage preceding flashover is larger than that on the negative half-cycle. This is shown on PL-34725, Fig. 1.

(2) 2" rod on ground plane.

- (a) Average flashover voltage - 218 KV (RMS).
- (b) For 7 flashover tests, all occurred on the negative half-cycle of the applied voltage wave.
- (c) All flashovers took place between the ground rod and the bushing dome.
- (d) The magnitude of the corona occurring on the negative half-cycle of the applied voltage wave increases in magnitude with the addition of the ground rod and is now slightly larger than that occurring on the positive half-cycle of applied voltage. This is shown on PL-34725, Fig. 2.

Observations: 138 KV type F bushing.

(1) Flat ground plane.

- (a) Average flashover voltage - 340 KV (RMS).

- (b) For 8 flashover tests, all occurred during the positive half-cycle of the applied voltage.
- (c) Corona occurring on the positive half-cycle of the applied voltage was many times larger than that on the negative half-cycle. This is shown on PL-34726, Fig. 3.
- (d) Corona was observed only at the bushing dome as shown by PL-34727.

(2) 6" rod on ground plane.

- (a) Average flashover voltage - 343 KV (RMS).
- (b) For 5 flashover tests where polarity was determined, 4 occurred during the positive half-cycle of the applied voltage and 1 during the negative.
- (c) For 10 flashover tests, 5 occurred between the dome and ground rod and 5 between the dome and ground plane.
- (d) The magnitude of the corona on both half-cycles of the applied voltage wave are nearly equal.
- (e) Visual observations showed corona discharges from both the bushing dome and the ground rod.

(3) 10" rod on the ground plane.

- (a) Average flashover voltage - 318 KV (RMS).
- (b) For 7 flashover tests where the polarity was determined, all took place on the negative half-cycle of the applied voltage wave.
- (c) All flashovers were between the bushing dome and the ground rod.
- (d) The magnitude of corona as shown on PL-34726, Fig. 4 appears to be approximately the same magnitude for both half-cycles of the applied voltage wave.
- (e) Corona was observed on both the bushing dome and ground rod prior to flashover as shown in PL-34728.

(4) 14" rod on the ground plane.

- (a) Average flashover voltage - 268 KV (RMS).
- (b) All flashovers were between the ground rod and bushing dome.
- (c) Corona discharge was visible only on the ground rod.

(5) 16" rod on the ground plane.

- (a) Average flashover voltage - 250 KV (RMS).

- (b) All flashovers were between the ground rod and bushing dome.
- (c) Corona was observed only on the ground rod prior to flashover as shown on PL-34729 except for a small brush discharge near the lifting lug on the bushing dome. This was eliminated by use of a small shield as shown on PL-34730. The introduction of this shield did not change the flashover values.

Discussion:

From the above observations and the flashover data of Table 5, the following conclusions can be drawn:

- 1) For the 73 KV bushing, the flashover values are lowered by the presence of a 2" ground rod while for the 138 KV bushing, a 6" ground rod did not appreciably effect the flashover. With the ground rod extended to 10" and larger values, the flashover values were somewhat reduced.
- 2) The polarity of flashover depended on the length of the ground rod. When the ground rod was 10" or more for the 138 KV bushing, flashover always occurred during the negative half-cycle of the applied voltage waves while with the 6" ground rod, flashovers of both polarity were noted and with no ground rod, only positive polarity flashovers occurred. With the 73 KV bushing, flashovers of both polarity were noted when no ground rod was present and only negative polarity flashovers occurred when the 2" ground rod was used.
- 3) In all cases, the magnitude of the corona observed on the negative half-cycle of the applied voltage wave was smaller than the positive when no ground rod was present, but increased in magnitude to be equal to or greater than the positive corona in the presence of a ground rod.
- 4) Corona was observed on both the bushing dome and ground rod except where very long ground rods were used. In this case, 14" and 16". Then corona was observed only on the ground rod.

From the above observations and conclusions, certain facts relating to the breakdown mechanism became clear. For the first case where no ground rod is present, the flashover always occurs on the positive half-cycle of the applied voltage wave for the 138 KV type F bushings. This means the bushing dome will be the anode and from the observations of visual corona, as well as corona current measurements, it becomes evident that the flashover is initiated from the anode. The mechanism involved will then be that of the positive streamer formation. Apparently, it is not quite this simple for the 73 KV type F bushing since in this case, flashovers of both polarities occur. Remembering that no corona was observed on the ground plane prior to flashover and it would be difficult to conceive that sufficiently high gradients would exist on the flat ground plane to cause corona formation, it seems likely that both the positive

and negative polarity breakdowns would be initiated at the bushing dome, the anode for positive polarity flashover and the cathode for negative. Referring to Tables 1 and 3, it can be seen that the positive polarity impulse flashover voltages are 425, 425, 425 and 457 KV while the negative polarity impulse flashover voltages are 457, 487 and 487 KV. It is evident that in one case at least, the positive and negative flashover voltages are equal. Now with sixty-cycle voltage applied, it seems very probable that under favorable conditions and the long time voltage applications (approximately 8300 μ s for each polarity on each half wave compared to 40 μ s to half value for the impulse wave) that now and then flashover would be initiated when the bushing dome was the cathode. If this is the case, then either the positive streamer mechanism when the bushing dome is the anode or the avalanche-retrograde-streamer mechanism when the bushing dome is the cathode, will initiate the flashover process.

In the second case, where a ground rod of sufficient length to cause a lowering of the flashover voltage is present, all flashovers take place on the negative half-cycle of the applied voltage wave. In this case, the voltage gradient at the rod tip is sufficiently great to initiate at least a localized breakdown as was shown by the corona emanating from it. With the lowering of the flashover values, it would be very difficult to conceive of a cathode initiated breakdown from the bushing dome since it is difficult for this mechanism to take place even at higher voltages. In fact for the 138 KV bushing where no ground rods were present, not a single flashover appears to have been initiated by this cathode mechanism so now with the lower voltage available, it is quite certain that this is not the mechanism involved. It seems quite likely then, that the mechanism must be initiated from the ground rod, since the bushing dome is the cathode during all flashovers. This means that the ground rod is the anode and the positive streamer formation from this ground rod will initiate flashover.

In the third case, where a ground rod is present, as for the 6" ground rods with the 138 KV bushings, and yet a lowering of the flashover values does not take place, flashovers of both polarities occur. In this specific case, it can be seen from Table 5 under the data where no ground rod is present, all flashovers occurred during the positive half-cycle of the applied voltage wave and it was explained that the flashover mechanism was initiated by the positive streamer formation from the anode (bushing dome). It was also shown that when the 10" ground rod was present, the mechanism involved was that of positive streamer formation from the ground rod and all flashovers took place during the negative half-cycle of the applied voltage wave. Now in this case, where both positive and negative polarity flashovers occur and a 6" ground rod is present, the flashover mechanism could be either initiated from the ground rod, or the bushing dome, depending on the critical conditions existing at each electrode. Since the ground rod is apparently not long enough for it to predominate in initiating the flashover and is not small enough so the bushing dome can initiate all the flashovers, the flashover mechanism must then be that of positive streamer formation either from the bushing dome as the anode when the flashover occurs on the positive half-cycle of the applied voltage wave, or from the ground rod as the anode when the flashover occurs on the negative half-cycle of the applied voltage wave.

General Discussion:

It can be seen from the values plotted on 106HA492 that the effect of the ground rod on the average flashover values for impulse and sixty-cycle tests is very different. For example, a very rapid reduction in the negative polarity impulse flashover voltage is apparent when the ground rod is present, while for the same ground rod lengths only a very small reduction in the average sixty-cycle flashover values is found. According to the theory previously presented, the mechanism of the bushing flashover in the presence of a ground rod for negative polarity impulse and sixty-cycle applied voltage is the same. The question then arises, why is the effect of the ground rod so different under these two voltage conditions? The answer to this must be the presence of a space charge condition under the sixty-cycle voltage that is absent when the negative polarity impulse voltage is applied. In order to establish the possibility of a space charge, it is necessary to review what is known about the corona starting voltages of a rod in air. Previous tests reported in 50TP1892 show that under sixty-cycle voltage conditions, the corona starting voltage of a rod-to-plane gap is lower on the negative half-cycle of the applied voltage wave than on the positive. Further, it is known that for the rod-to-plane gap, the impulse corona starting voltage for positive and negative polarities are approximately the same. This fact would seem to indicate that a discrepancy exists in the test results where it was reported that for positive polarity impulse applied to the bushing, no corona from the ground rod was observed, yet for negative polarity impulse applied, corona did exist on the ground rod at very low values. This difference in corona starting voltages surely does not exist, but rather the apparent discrepancy of results is due to our definition of the corona starting values. For the bushing test results, rather poor observation conditions existed and the first sign of corona visible to the observer was that of the streamer type corona formation some hundreds or even thousands of times the minute type corona discharge measured by sensitive detection technique or observed under ideal conditions. This discrepancy in the definition of the corona starting voltages, however, does not in any way invalidate our previous test results since the bushing flashover mechanism for impulse voltage conditions must depend on the streamer type formation of corona discharge rather than the very small type corona mentioned here.

The formation of the space charge in the vicinity of the ground rod causing the apparent difference in the ground rod effect between negative impulse and the sixty-cycle flashover voltages must take place in a manner very similar to that reported in 50TP1818 on the sixty-cycle sphere-to-plane breakdown in air. This space charge mechanism can be described as follows. When the voltage gradient on the ground rod has increased to a sufficiently high value, corona will first occur while the ground rod is negative. The electrons in the electron avalanche will be repelled away from the rod and ionize as they travel until the external field drops to a value of 15 KV/cm or less. At this time, the electrons will drift toward the anode until they combine with neutral molecules, in some $.6 \times 10^{-6}$ sec., the mean time of attachment of an electron in air, to form negative ions. These negative ions continue to drift toward the anode away from the ground rod with a relatively low mobility of approximately 2.2 cm/sec/volt/cm until the polarity of the rod is reversed on the following half-cycle of applied voltage, at which time these negative ions reverse their direction of travel and

go back toward the rod. As the voltage is continually raised, the repetition of this process will build up the negative ion space charge in the vicinity of the ground rod. When the voltage gradient at the tip of the ground rod has increased to a value sufficiently high, positive corona streamer will begin to form. It was shown previously that the positive streamer is essentially the propagation of a positive ion space charge into the gap. This positive ion space charge will tend to draw the negative ions, from the negative ion space charge in the vicinity of the rod, into it and as a consequence of this action be neutralized. This neutralization of the positive ion space charge will prevent the streamer from propagating and inhibit the breakdown of the gap. On each succeeding half-cycle, the negative ion space charge will be replenished and tend to inhibit the positive streamer breakdown on the following half-cycle until the voltage has been raised to such a value that the negative ion space charge can no longer neutralize the self propagating positive ion space charge and breakdown by positive streamer formation takes place. This type space charge formation will tend to minimize the effect of the ground rod on the sixty-cycle flashover of the bushing.

For the negative polarity impulse flashover of the bushing, the ground rod is, of course, positive polarity only, so that there is no possibility of setting up a negative ion space charge to inhibit the positive streamer formation of the ground rod. Consequently, the effect of the ground rod should become very pronounced as its length is increased.

In comparing the positive polarity impulse flashover voltage with the sixty-cycle flashover voltages of the 138 KV bushing where no ground rod is present, an impulse ratio of 1.8 is found. For both the sixty-cycle and impulse voltages, the positive streamer mechanism initiates flashover but, under the sixty-cycle voltage condition a negative ion space charge is formed and oscillates in the space in rhythm with the sixty-cycle voltage. If this space charge is located a short distance away from the anode when the voltage is near crest, it increases the gradient at the anode sufficiently to result in a positive streamer formation at lower applied voltage. In a case such as this, the negative ion space charge, because of its location, will not be able to neutralize the positive ion space charge of the positive streamer and flashover will take place. It is the presence and location of the negative ion space charge under the sixty-cycle voltage condition that results in lower flashover values for sixty-cycle applied voltage than for positive polarity impulse.

It was shown in 52TP20 that a negative ion space charge actually raised the sixty-cycle flashover when a sharp lip was on the bushing dome. In this case, the location of the negative ion space charge must have been very close to the bushing dome so that the positive streamers, once formed, could be neutralized by this negative ion space charge.

A detailed study, presented in report 50TP1818, shows how the presence and location of a negative ion space charge can affect the sixty-cycle breakdown strength of a non-uniform field gap in air. In this report, the increase or decrease in the sixty-cycle strength of the non-uniform field gap is explained on the basis of the negative ion space charge location.

CONCLUSIONS:

A. Positive polarity impulse voltage applied.

1. The flashover is initiated by positive streamer formation from the anode (bushing dome).
2. The presence of ground rods effect neither the flashover values nor the corona starting voltage of the bushing.

B. Negative polarity impulse voltage applied.

1. With no ground rod present, the flashover mechanism is initiated by the retrograde-streamer formation from the bushing dome.
2. The presence of a ground rod appreciably lowers both the corona starting and flashover voltages of the bushing.
3. With a ground rod present, the flashover mechanism is initiated by the positive streamer formation starting at the ground rod.

C. Sixty-cycle voltage applied.

1. With no ground rod present, the flashover is initiated by either positive streamer formation from the anode (bushing dome) when flashover occurs on the positive half-cycle of the applied voltage wave, or by the avalanche-retrograde-streamer formation from the cathode (bushing dome) when flashover occurs on the negative half-cycle of the applied voltage wave.
2. Where a ground rod of sufficient length to cause a lowering of the sixty-cycle flashover voltage is present, the flashover is initiated by the positive streamer mechanism from the anode. The anode in this case is the ground rod.
3. Where the ground rod is present and not sufficiently long to cause a reduction in the flashover voltage, the flashover will be initiated by positive streamer formation from the anode. The anode in this case will be the ground rod if flashover takes place on the negative half-cycle of the applied voltage wave or the bushing dome if flashover takes place on the positive half-cycle of the applied voltage wave.

TABLE 1
IMPULSE TESTS ON 73 KV BUSHING

Positive Polarity Impulse

No Rod on Ground Plane					2" Rod on Ground Plane					Flash to Grd. Rod
Film No.	KV Crest	Corona MA	Streamer	Flash- over	Film No.	KV Crest	Corona MA	Streamer	Flash- over	
24	365	---	yes	no	34	365	---	yes	no	---
25	395	---	yes	no	--	395	---	yes	no	---
26	425	---	yes	yes	--	425	---	yes	yes	yes
--	365	---	yes	no	--	365	---	yes	no	---
--	395	---	yes	no	--	395	---	yes	no	---
--	425	---	yes	yes	--	425	---	yes	yes	no
--	365	---	yes	no	--	365	---	yes	no	---
--	395	---	yes	no	--	395	---	yes	no	---
--	425	---	---	yes	--	425	---	---	yes	no
50	365	583	yes	no	42	305	583	yes	no	---
51	395	589	yes	no	43	335	565	yes	no	---
52	425	595	yes	no	44	365	595	yes	no	---
53	457	---	---	yes	45	395	595	yes	no	---
					46	425	---	---	yes	no

Corona on dome.

Corona on dome.

Average corona streamer start = 365 KV. Average corona streamer start = 345 KV.
Average flashover = 435 KV. Average flashover = 425 KV.

TABLE 2
IMPULSE TESTS ON 138 KV TYPE F BUSHING

Positive Polarity Impulse

No Rod on Ground Plane			Rod on Ground Plane				
KV	Corona	Flash-	KV	Corona	Length of	Flash-	F.O. to
Crest		over	Crest		Grd. Rod	over	Grd.Rod
800	Dome & Porcelain	---	800	Dome	10"	---	---
850	-----	yes	850	"	10"	yes	yes
800	Dome & Porcelain	---	800	Dome	10"	---	---
850	" "	yes	850	"	10"	yes	yes
			Corona start (dome) - 800 KV. Flashover (average) - 850 KV.				
800	Dome	---					
850	"	---	850	Dome	6"	---	---
900	-----	yes	900	"	6"	yes	yes
			850	Dome	6"	yes	yes

Ave. corona streamer (dome) - 800 KV. Ave. corona streamer start (dome) - 850 KV.
Ave. flashover - 866 KV. Ave. flashover - 875 KV.

TABLE 3
IMPULSE TESTS ON 73 KV BUSHING
Negative Polarity Impulse

No Rod on Ground Plane					2" Rod on Ground Plane					Flash to Grd. Rod
Film No.	KV Crest	Corona MA	Streamer	Flash- over	Film No.	KV Crest	Corona MA	Streamer	Flash- over	
4	365	600	yes	no	9	305	610	yes	no	---
5	395	600	yes	no	10	335	605	yes	no	---
6	425	555	yes	no	11	365	---	---	yes	yes
7	457	610	yes	yes						
-	365	---	yes	no	14	335	605	yes	no	---
-	395	---	yes	no	15	365	610	yes	no	---
-	425	---	yes	no	16	395	---	---	yes	yes
-	457	---	yes	no						
-	487	---	---	yes						
-	365	---	yes	no	--	365	---	yes	no	---
-	395	---	yes	no	--	395	---	---	yes	yes
-	425	---	yes	no						
-	457	---	yes	no						
-	487	---	---	yes						

Corona on dome.

Corona on dome and ground rod.

Average corona streamer start = 365 KV. Average corona streamer start = 335 KV.
Average flashover = 477 KV. Average flashover = 385 KV.

TABLE 4

IMPULSE TEST ON 138 KV TYPE F BUSHING

Negative Polarity Impulse

No Rod on Ground Plane			Rod on Ground Plane				
KV Crest	Corona	Flash- over	KV Crest	Corona	Length of Grd.Rod	Flash- over	F.O. to Grd.Rod
750	Dome	---	400	Grd. Rod	10"	---	---
800	"	---	450	" "	10"	---	---
850	"	---	500	" "	10"	---	---
900	"	---	550	-----	10"	yes	yes
950	"	yes					
			400	Grd. Rod	10"	---	---
750	Dome	---	450	" "	10"	---	---
800	"	---	500	" "	10"	---	---
850	"	yes	550	-----	10"	yes	yes
Ave. corona streamer start=750 KV.			Ave. corona streamer start (Grd.Rod)=400 KV				
Ave. flashover (Ave.) =900 KV.			Ave. flashover =550 KV				
			550	Grd. Rod	6"	---	---
			600	" "	6"	---	---
			650	-----	6"	yes	yes
			550	Grd. Rod	6"	---	---
			600	" "	6"	---	---
			650	-----	6"	yes	yes
			Ave. corona streamer start (Grd. Rod)=550 KV.				
			Aver. flashover =650 KV.				

TABLE 5

SIXTY-CYCLE DATA ON BUSHING FLASHOVER

73 KV Bushing Type OF

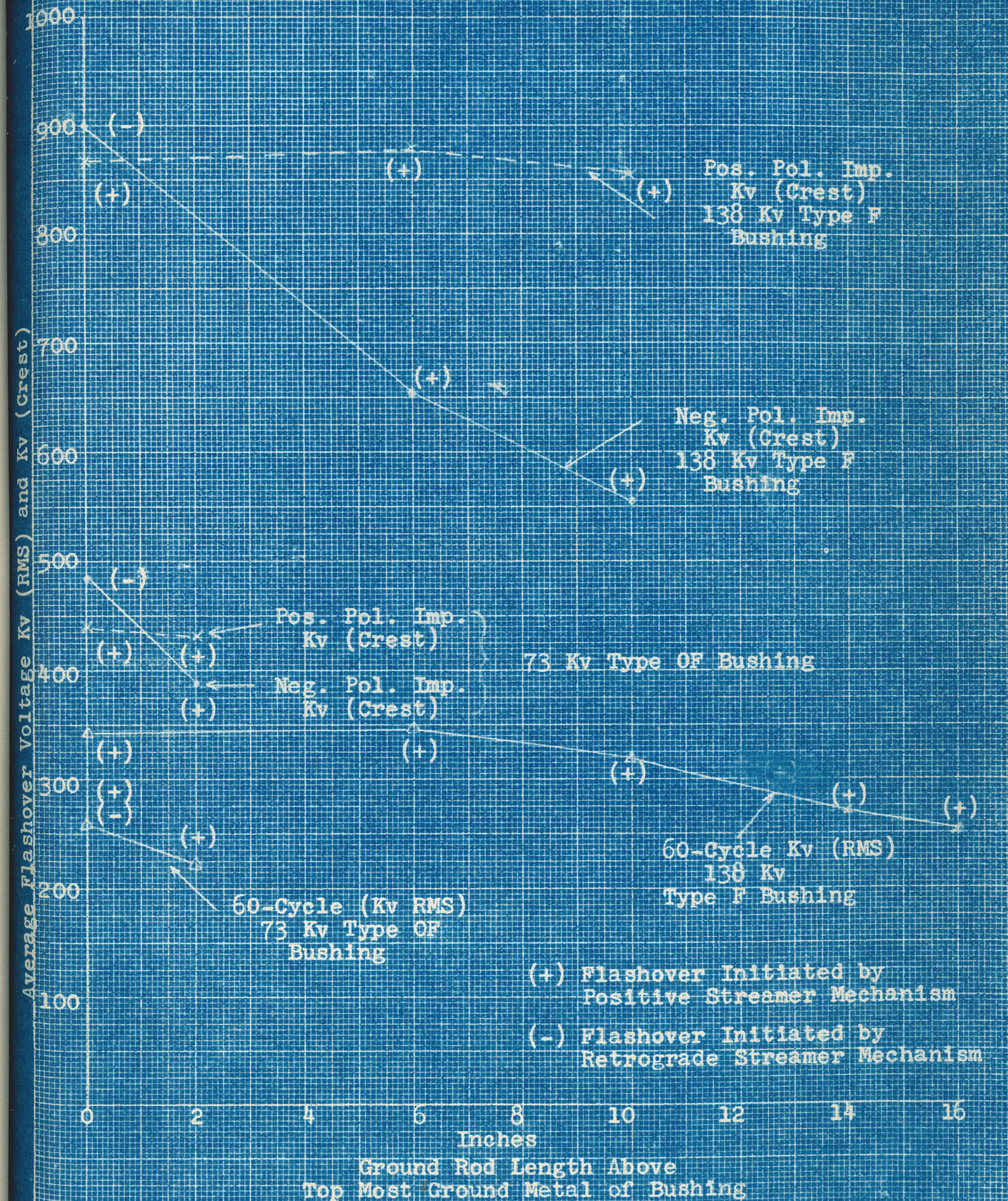
No Ground Rod				Rod on Ground Plane					
Film No.	Run No.	KV (RMS)	Polarity Flashover	Film No.	Run No.	KV (RMS)	Polarity Flashover	Length of Grd. Rod	Flash to Grd. Rod
--	-	246	-----	--	-	220	-----	2"	yes
--	-	256	-----	--	-	218	-----	2"	yes
--	-	250	-----	--	-	217	-----	2"	yes
2	1	---	Positive	1	1	---	Negative	2"	yes
	2	---	Negative		2	---	Negative	2"	yes
	3	---	Positive	4	1	---	Negative	2"	yes
3	1	---	Positive		2	---	Negative	2"	yes
	2	---	Positive		3	---	Negative	2"	yes
	3	---	Negative	6	1	---	-----	2"	yes
5	1	---	Positive		2	---	Negative	2"	yes
	2	---	Negative		3	---	Negative	2"	yes
Ave. = 251 KV				2" Ave. = 218 KV					

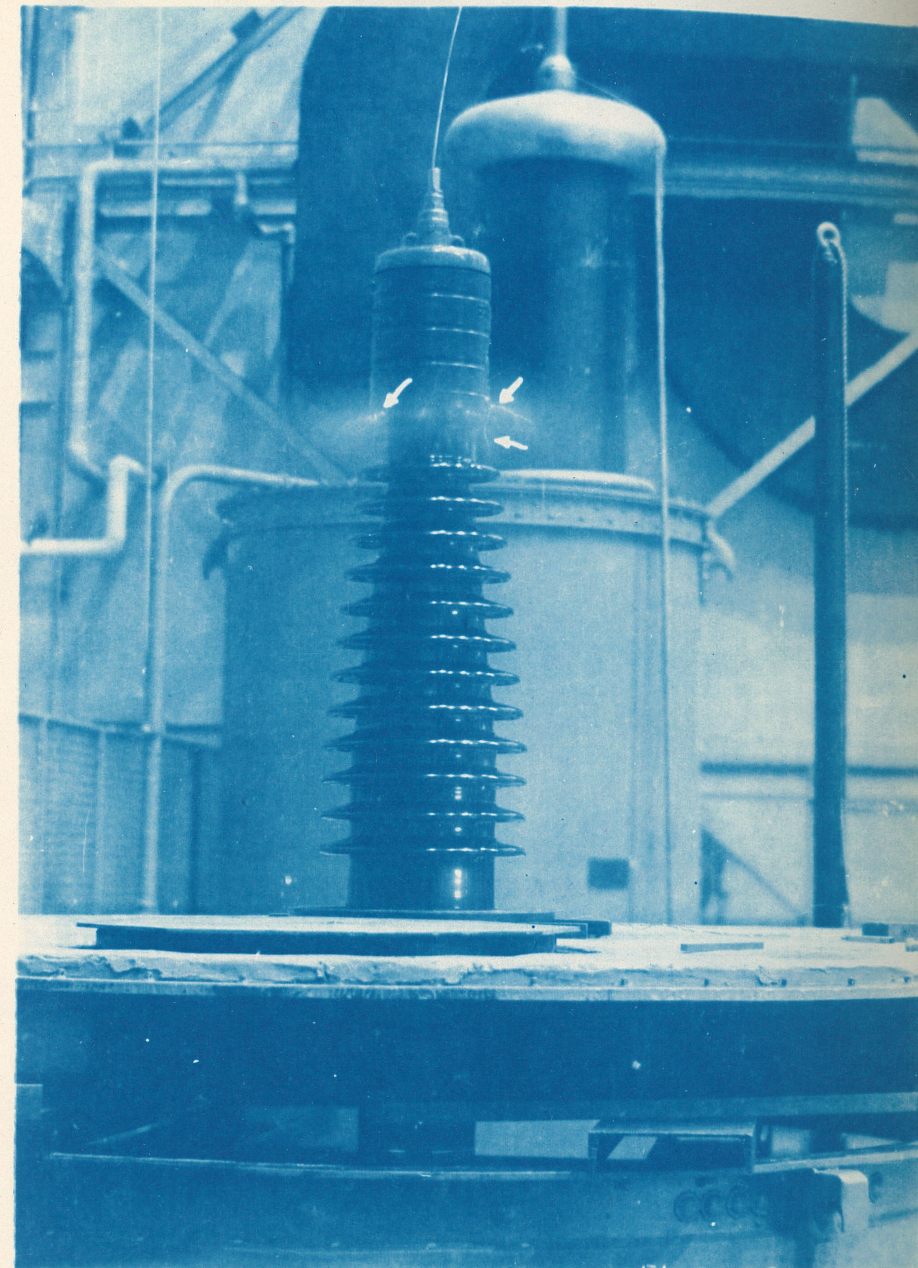
138 KV Bushing Type F

7	1	---	-----	8	1	---	Positive	6"	no
	2	---	Positive		2	---	Negative	6"	yes
	3	---	Positive		3	---	Positive	6"	yes
9	1	---	Positive	10	1	---	Positive	6"	no
	2	---	Positive		2	---	Positive	6"	no
12	1	353	Positive	--	-	345	-----	6"	yes
	2	353	-----	--	-	325	-----	6"	no
	3	353	-----	--	-	357	-----	6"	yes
13	-	333	-----	--	-	345	-----	6"	yes
	-	354	-----	--	-	345	-----	6"	no
	1	336	Positive	11	1	312	Negative	10"	yes
	2	333	Positive		2	316	Negative	10"	yes
	3	316	-----		3	312	Negative	10"	yes
	4	333	Positive	14	-	320	-----	10"	yes
	-	316	-----		1	320	Negative	10"	yes
--	-	341	-----		2	316	Negative	10"	yes
--	-	354	-----		3	320	Negative	10"	yes
--	-	345	-----		4	312	Negative	10"	yes
Ave. = 340 KV				--	-	320	-----	10"	yes
				--	-	320	-----	10"	yes
				--	-	270	-----	14"	yes
				--	-	266	-----	14"	yes
				--	-	254	-----	16"	yes
				--	-	246	-----	16"	yes

6" Ave. = 343 KV 14" Ave. = 268 KV
10" Ave. = 318 KV 16" Ave. = 250 KV

EFFECT OF GROUND ROD ON BUSHING FLASHOVER VOLTAGE

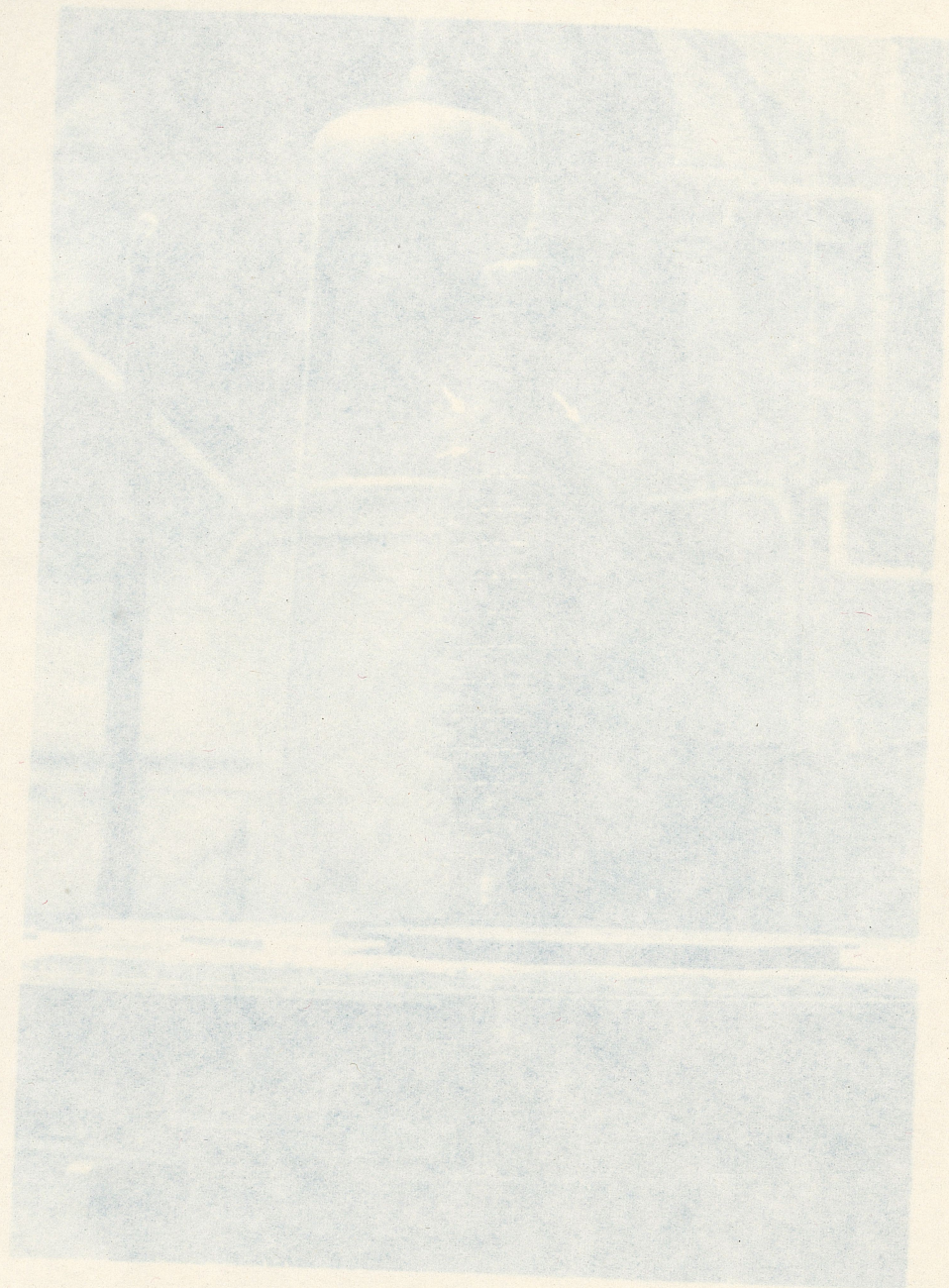




3365-38

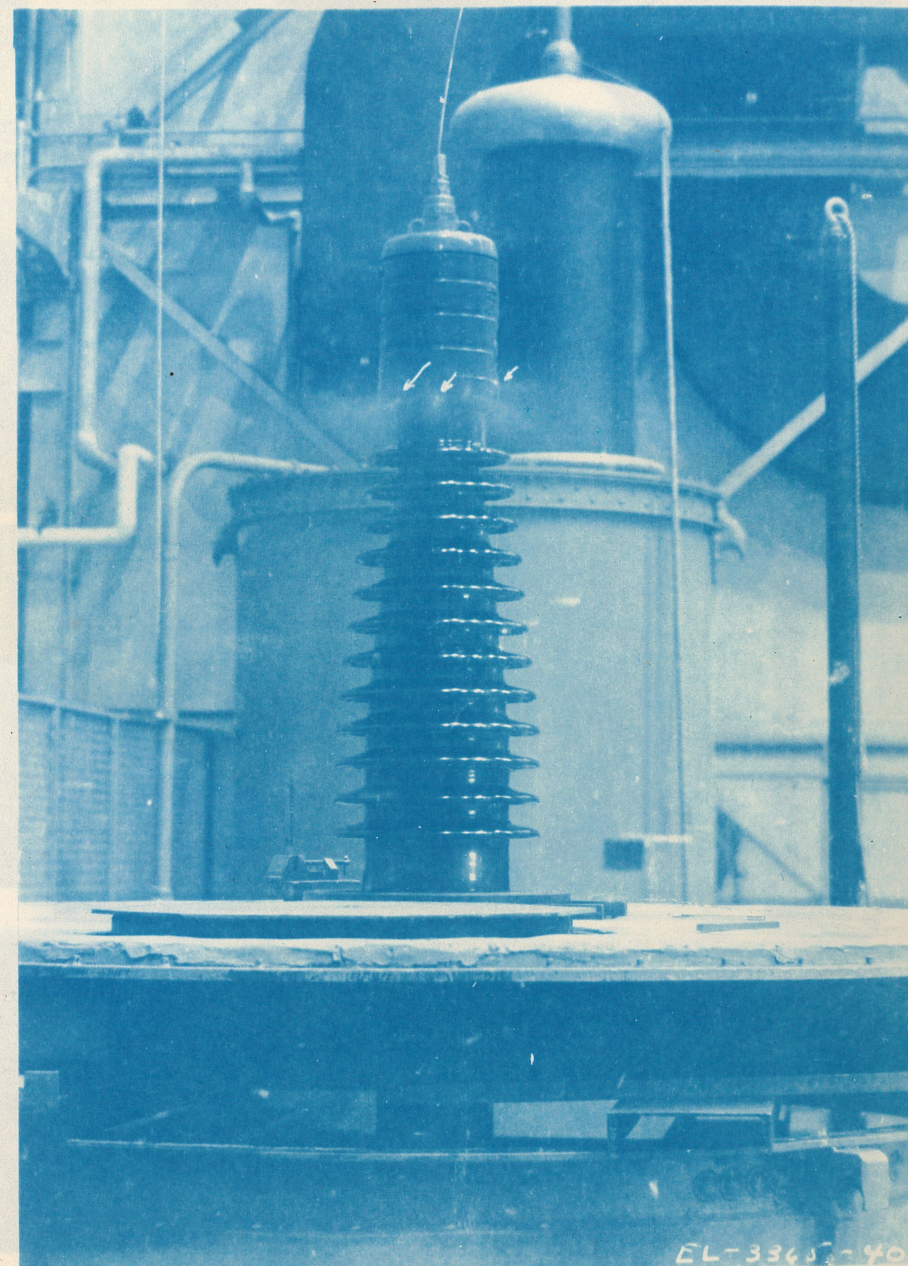
138 KV TYPE F BUSHING
 POSITIVE POLARITY IMPULSE VOLTAGE APPLIED
 CORONA STREAMERS FROM BUSHING DOME

PL-34721



3365-38
138 KV TYPE F BUSHING
POSITIVE POLARITY IMPULSE VOLTAGE APPLIED
CORONA STREAMERS FROM BUSHING DOME

PL-34722



3365-40

138 KV TYPE F BUSHING
POSITIVE POLARITY IMPULSE VOLTAGE APPLIED
CORONA STREAMERS FROM BUSHING DOME
10 INCH ROD ON GROUND PLANE

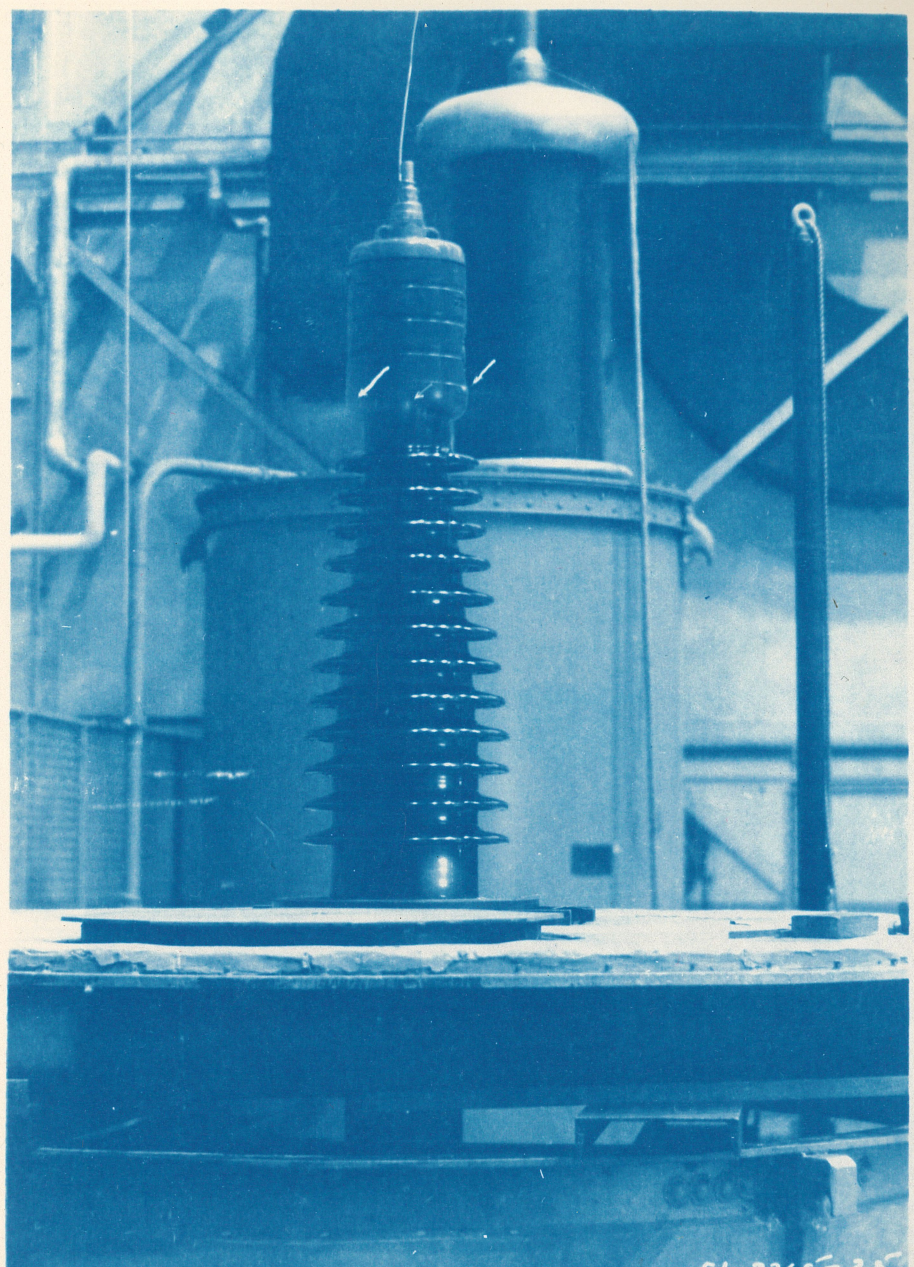
PL-34722



3365-40

138 KV TYPE F BUSHING
 POSITIVE POLARITY IMPULSE VOLTAGE APPLIED
 CORONA STREAMERS FROM BUSHING DOME
 10 INCH ROD ON GROUND PLANE

PL-34723

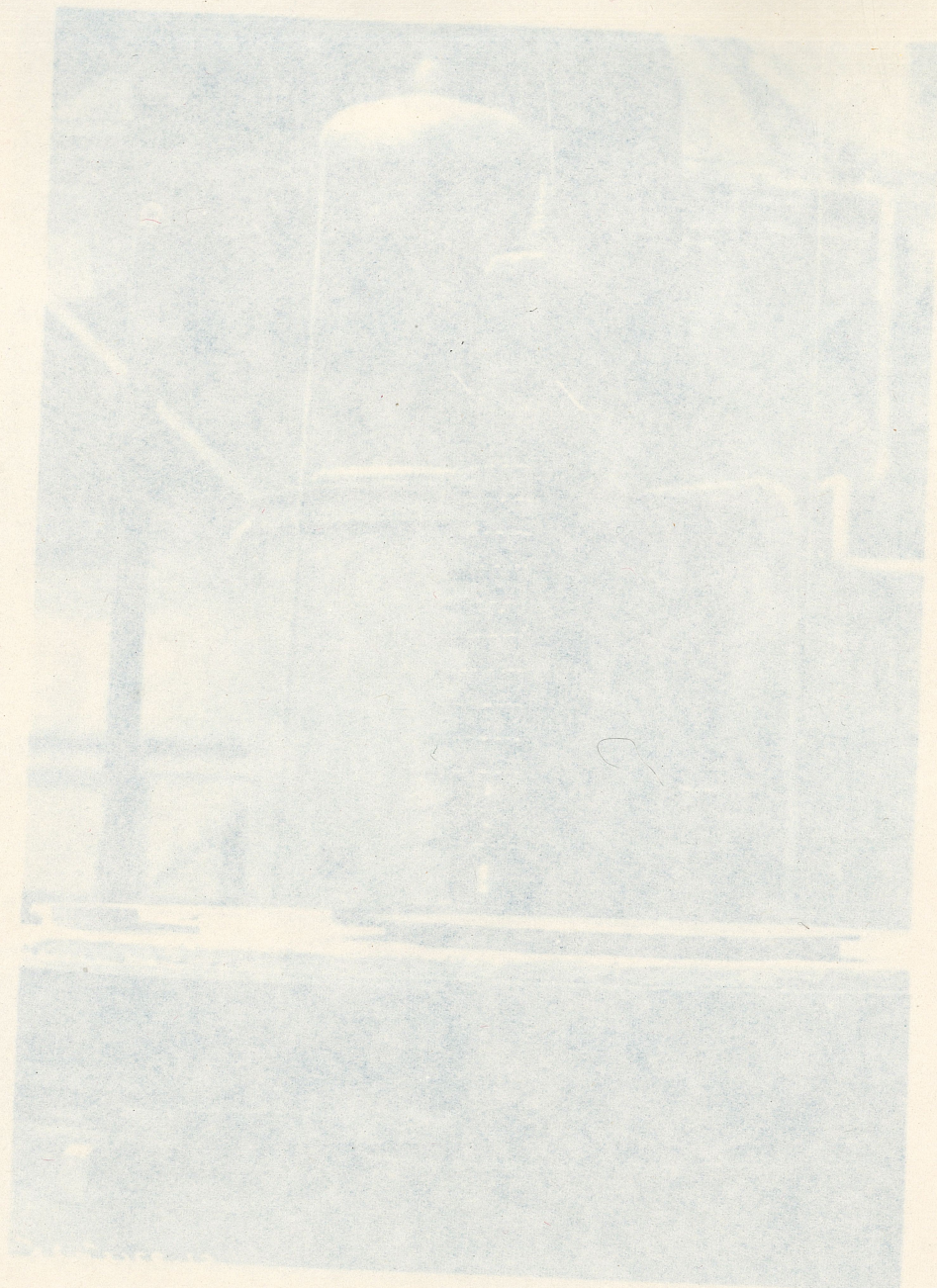


3365-25

138 KV TYPE F BUSHING
 NEGATIVE POLARITY IMPULSE VOLTAGE APPLIED
 CORONA STREAMERS FROM BUSHING DOME

138 KV TYPE F BUSHING
 NEGATIVE POLARITY IMPULSE VOLTAGE APPLIED
 CORONA STREAMERS FROM GROUND PLANE
 10 INCH ROD ON GROUND PLANE

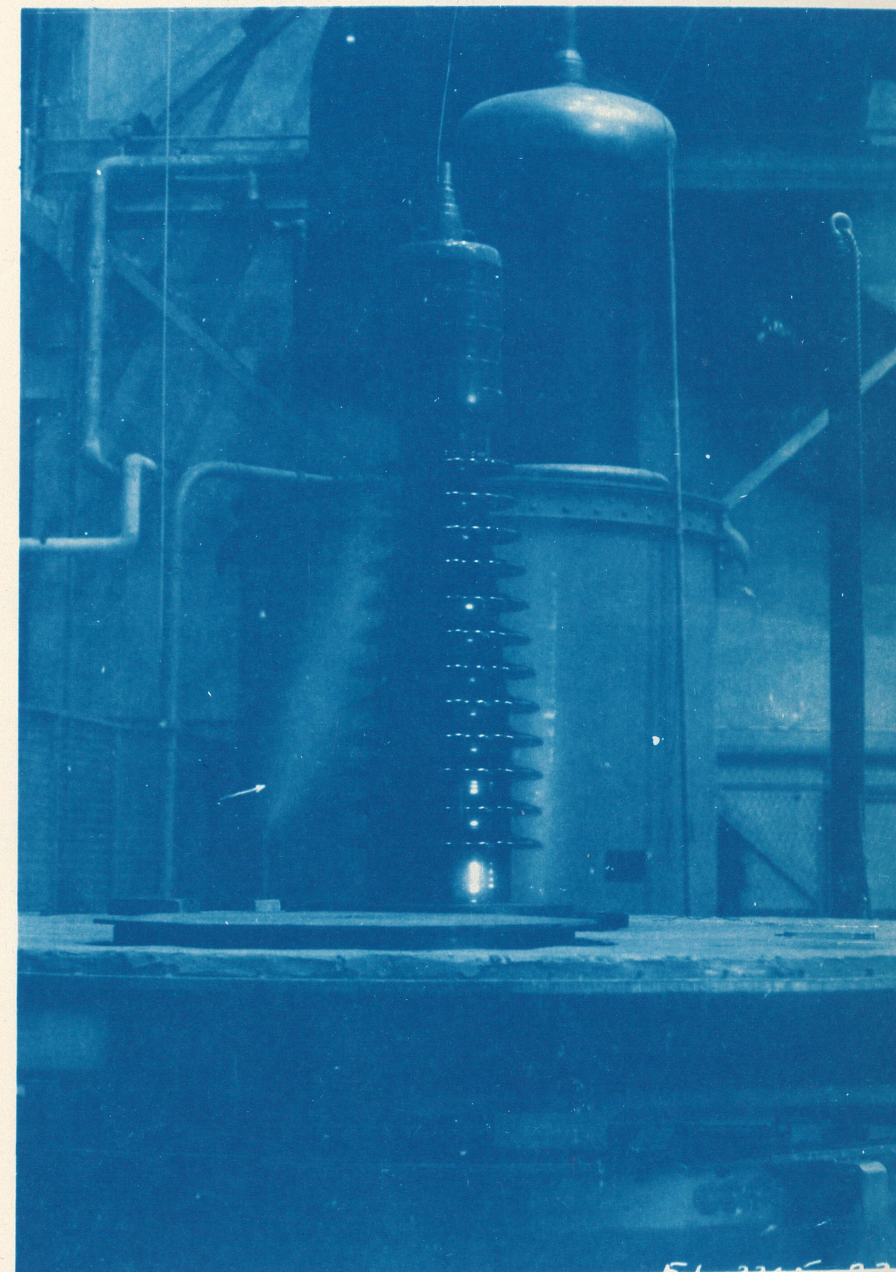
PL-34723



3365-23

138 KV TYPE F BUSHING
NEGATIVE POLARITY IMPULSE VOLTAGE APPLIED
CORONA STREAMERS FROM BUSHING DOME

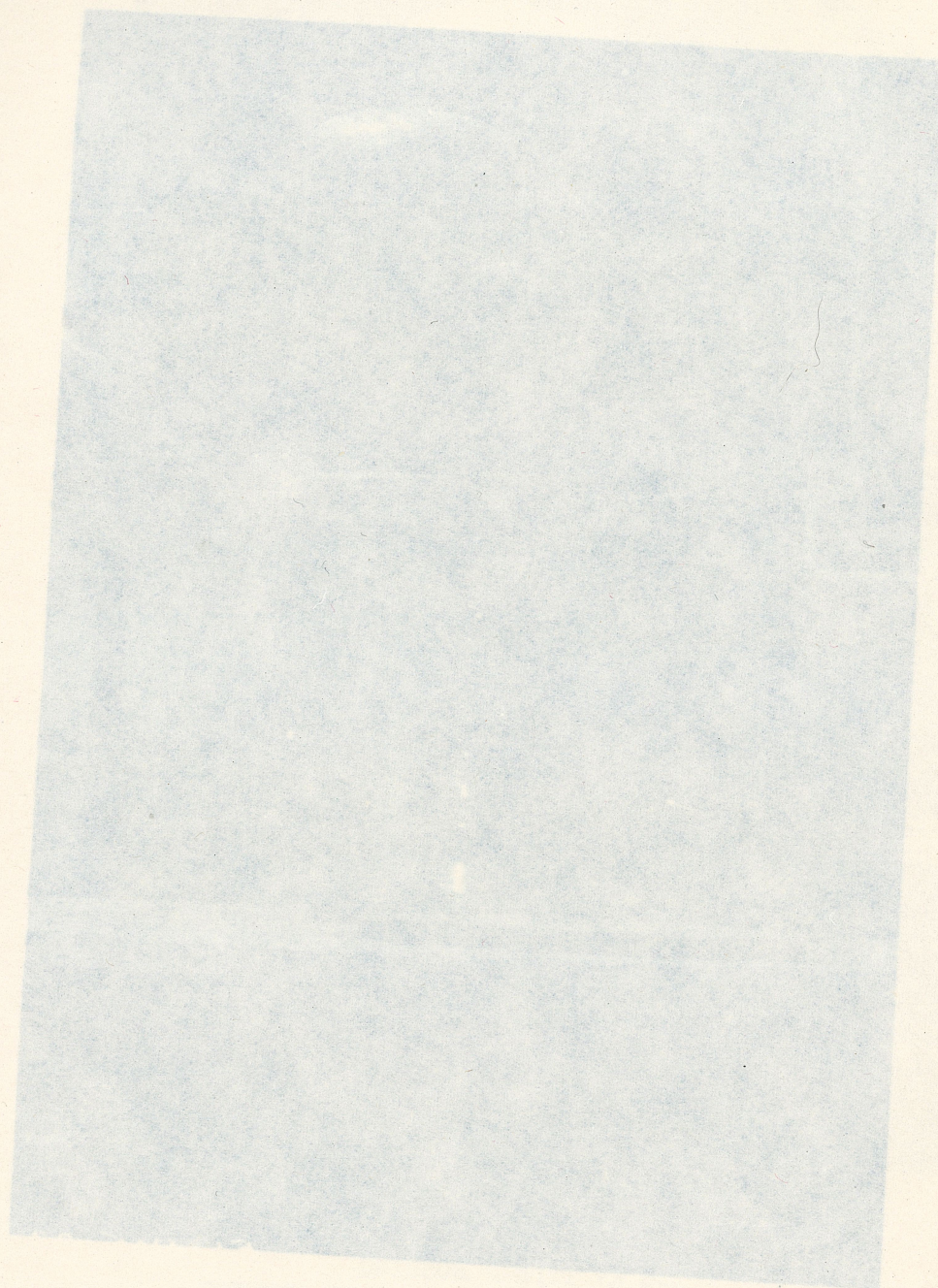
PL-34723



3365-23

138 KV TYPE F BUSHING
NEGATIVE POLARITY IMPULSE VOLTAGE APPLIED
CORONA STREAMERS FROM GROUND ROD
6 INCH ROD ON GROUND PLANE

PL-34724



3365-5
73 KV TYPE OF BUSHING
NEGATIVE POLARITY IMPULSE VOLTAGE APPLIED
CORONA STREAMERS FROM GROUND ROD
8 INCH ROD ON GROUND PLANE

PL-34725

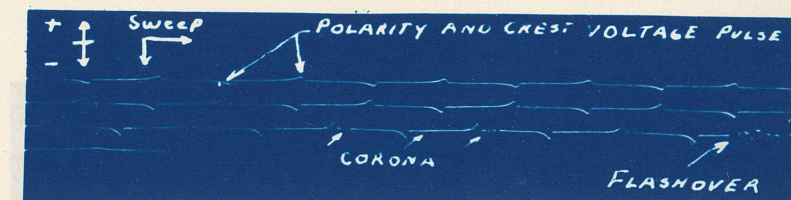


Fig. 1

3365-5
73 KV TYPE OF BUSHING
60 CYCLE CURRENT OSCILLOGRAM OF CORONA AND FLASHOVER
NO ROD ON GROUND PLANE



Fig. 2

3365-1
73 KV TYPE OF BUSHING
60 CYCLE CURRENT OSCILLOGRAM OF CORONA AND FLASHOVER
2 INCH ROD ON GROUND PLANE

PL-34725



Fig. 1

3365-2
138 KV TYPE F BUSHING
60 CYCLE CURRENT OSCILLOGRAM OF CORONA AND FLASHOVER
NO ROD ON GROUND PLANE



Fig. 2

3365-1
138 KV TYPE F BUSHING
60 CYCLE CURRENT OSCILLOGRAM OF CORONA AND FLASHOVER
3 INCH ROD ON GROUND PLANE

PL-34725

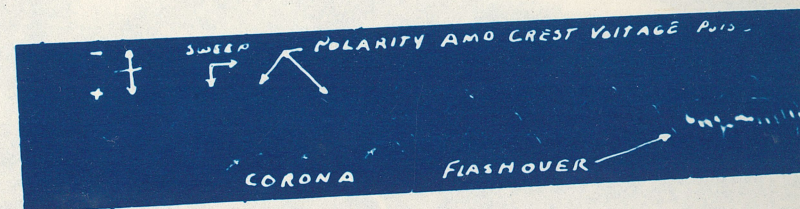


Fig. 3

3365-13
138 KV TYPE F BUSHING
60 CYCLE CURRENT OSCILLOGRAM OF CORONA AND FLASHOVER
NO ROD ON GROUND PLANE

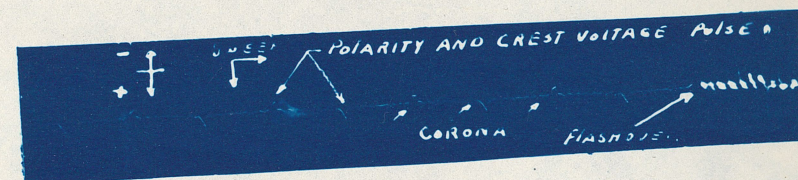


Fig. 4

3365-14
138 KV TYPE F BUSHING
60 CYCLE CURRENT OSCILLOGRAM OF CORONA AND FLASHOVER
10 INCH ROD ON GROUND PLANE

PL-34726

3365-14
138 KV TYPE F BUSHING
60 CYCLE VOLTAGE APPLIED
CORONA STREAMERS FROM BUSHING DOME

PL-34727



Fig. 3

3365-13

138 KV TYPE F BUSHING
60 CYCLE CURRENT OSCILLOGRAM OF CORONA AND FLASHOVER
NO ROD ON GROUND PLANE

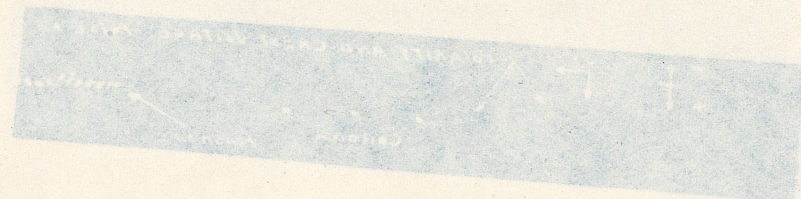
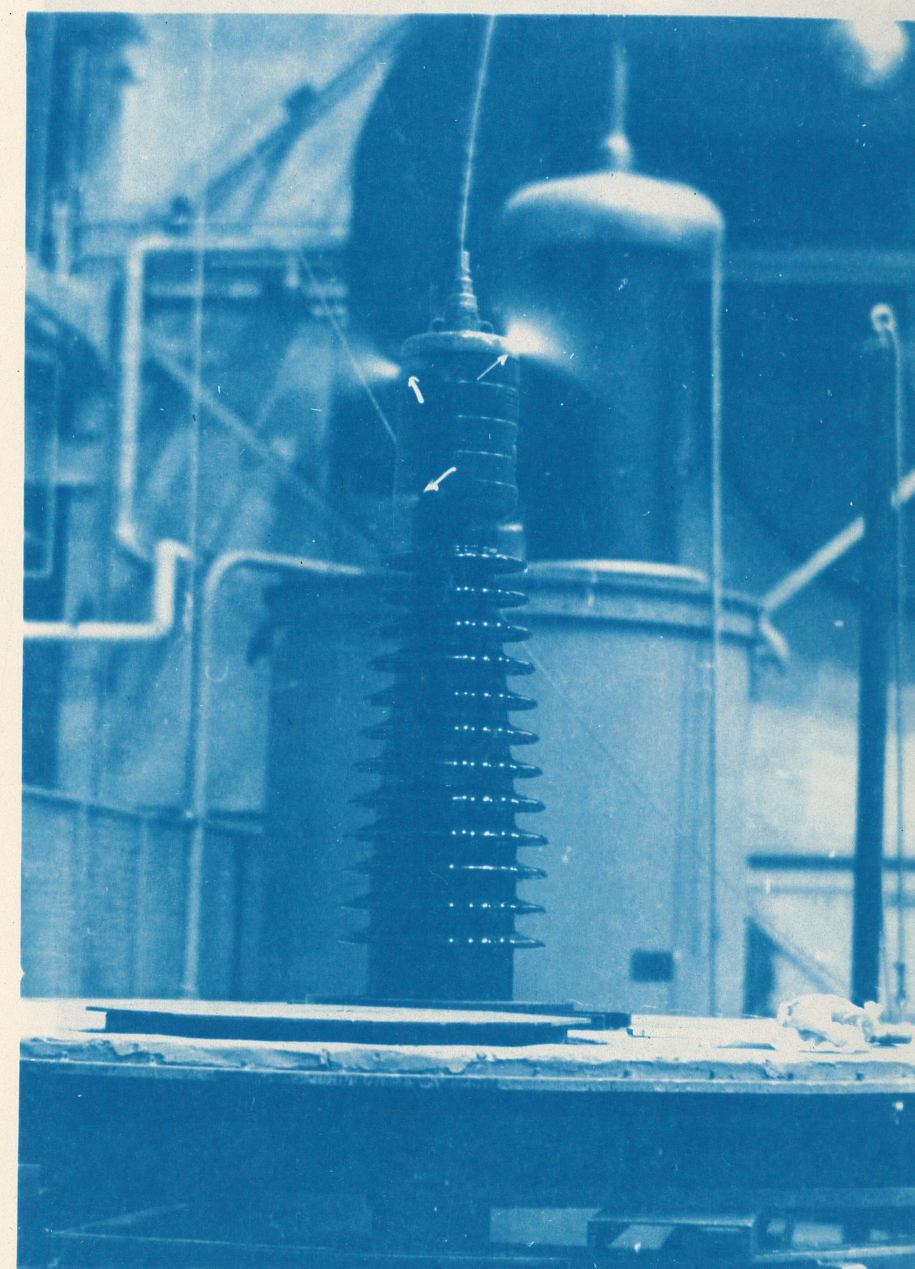


Fig. 4

3365-14

138 KV TYPE F BUSHING
60 CYCLE CURRENT OSCILLOGRAM OF CORONA AND FLASHOVER
10 INCH ROD ON GROUND PLANE

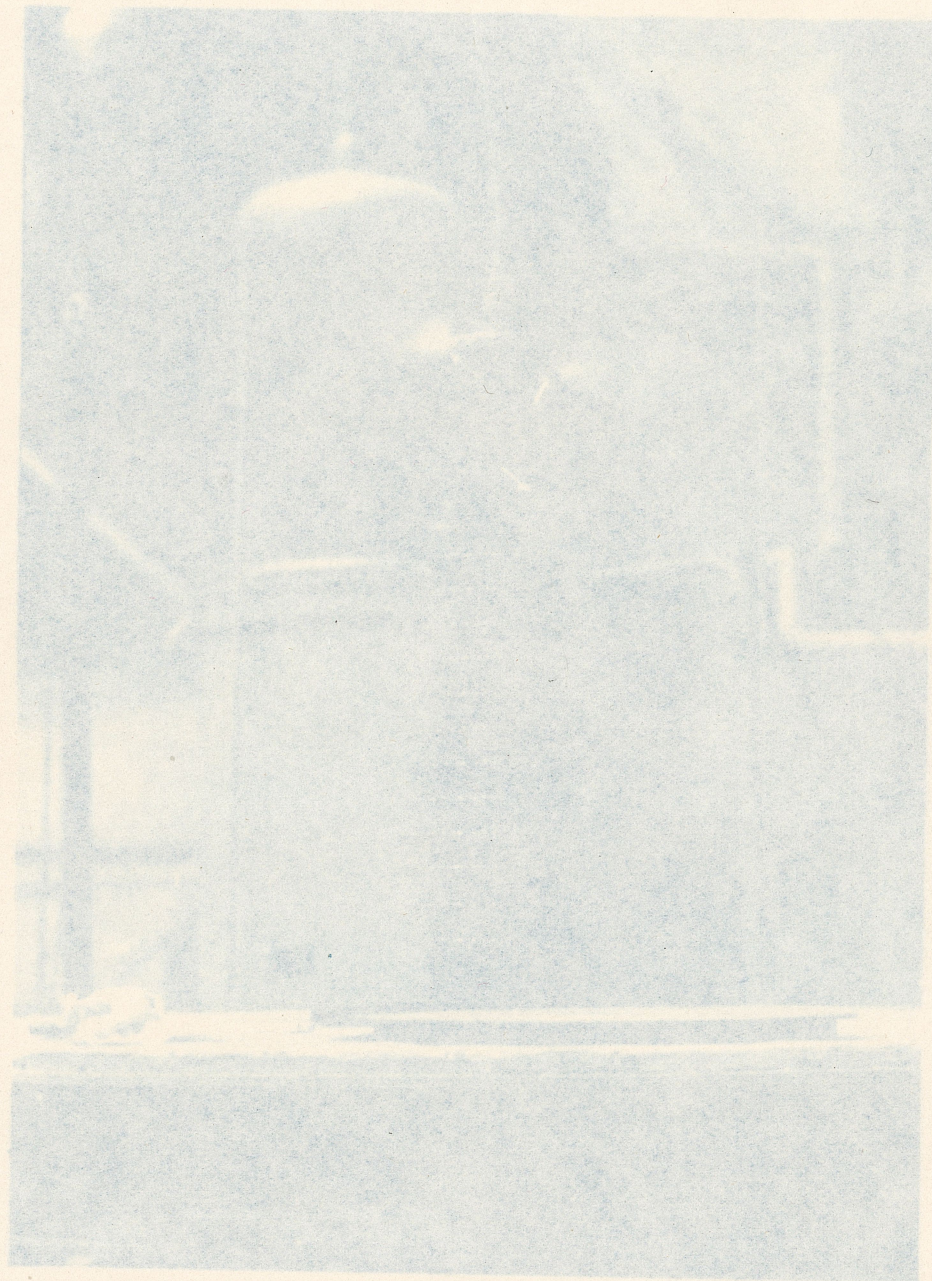
PL-34726



CORONA STREAMERS FROM BUSHING DOME AND GROUND PLANE
3365-14

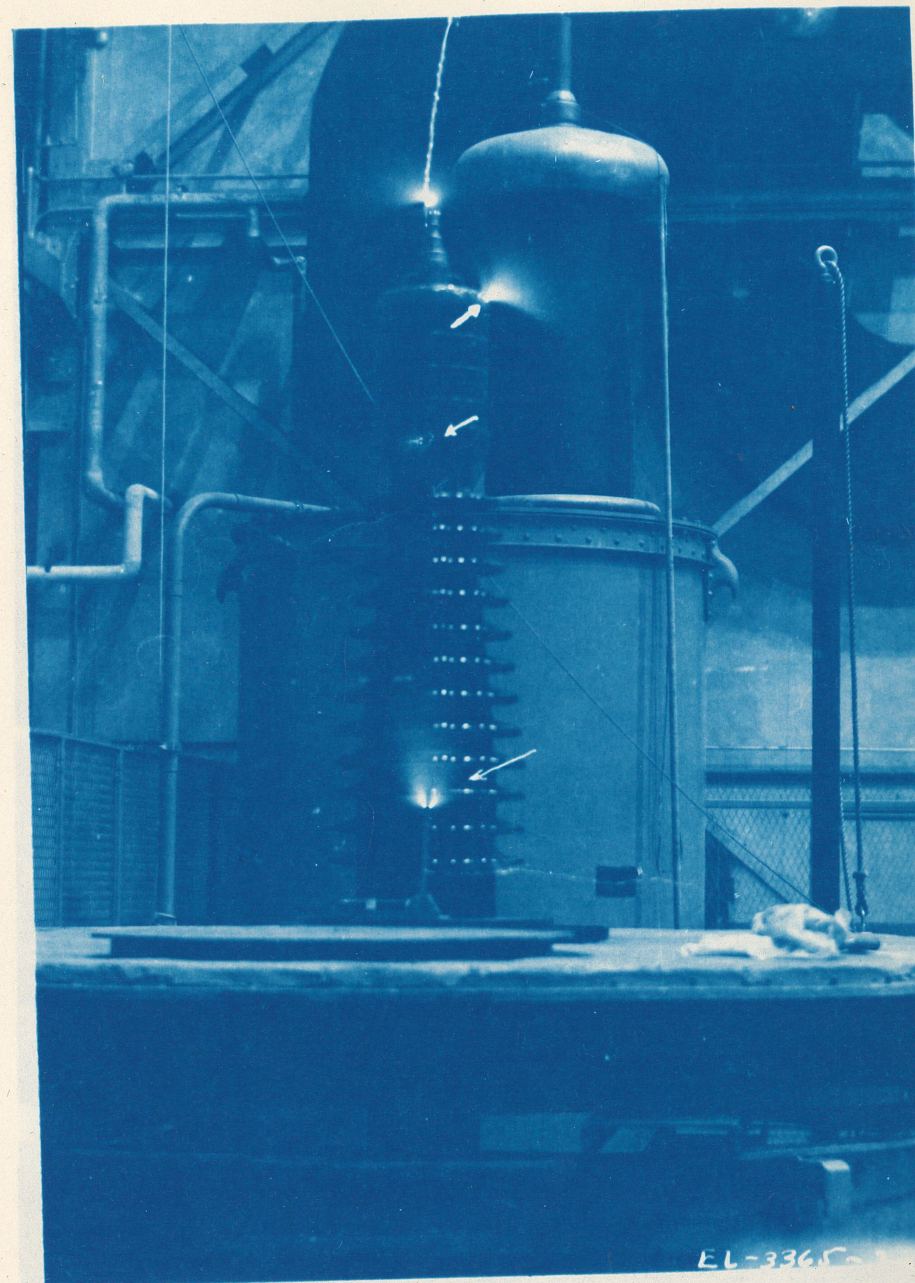
138 KV TYPE F BUSHING
60 CYCLE VOLTAGE APPLIED
CORONA STREAMERS FROM BUSHING DOME

PL-34727



3365-14
138 KV TYPE F BUSHING
60 CYCLE VOLTAGE APPLIED
CORONA STREAMERS FROM BUSHING DOME

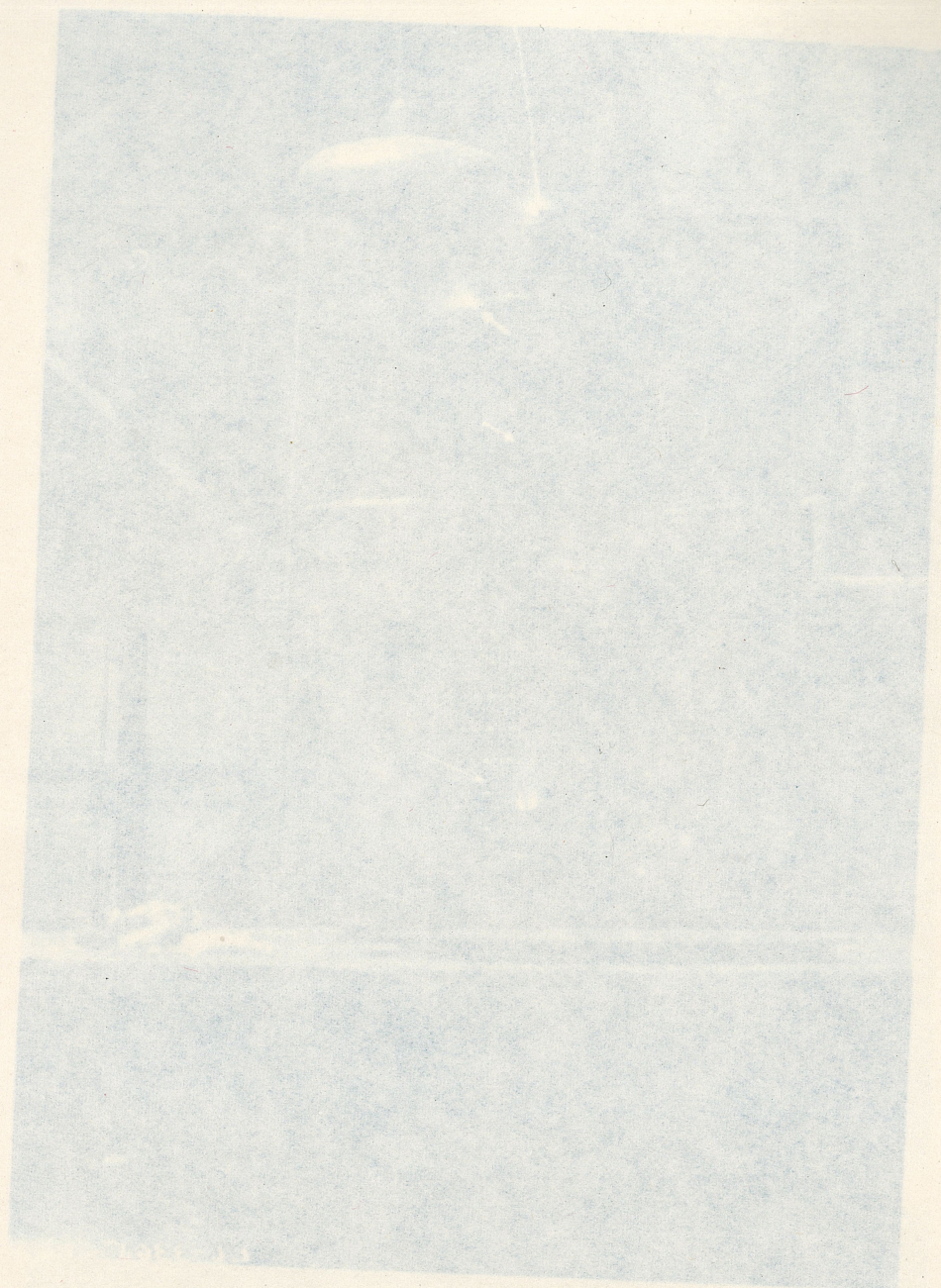
PL-34727



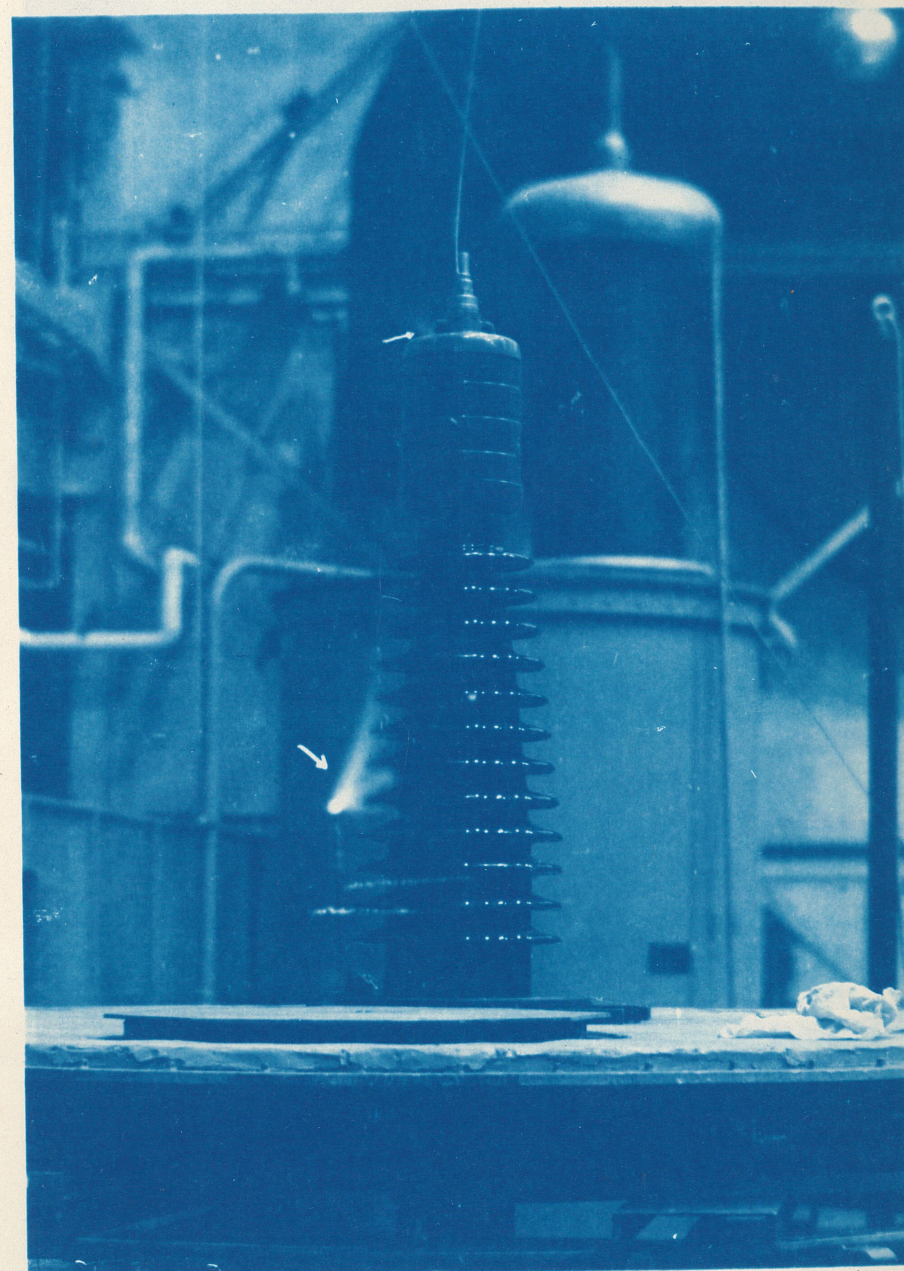
3365-2

138 KV TYPE F BUSHING
60 CYCLE VOLTAGE APPLIED
CORONA STREAMERS FROM BUSHING DOME AND GROUND ROD -
10 INCH ROD ON GROUND PLANE

PL-34728

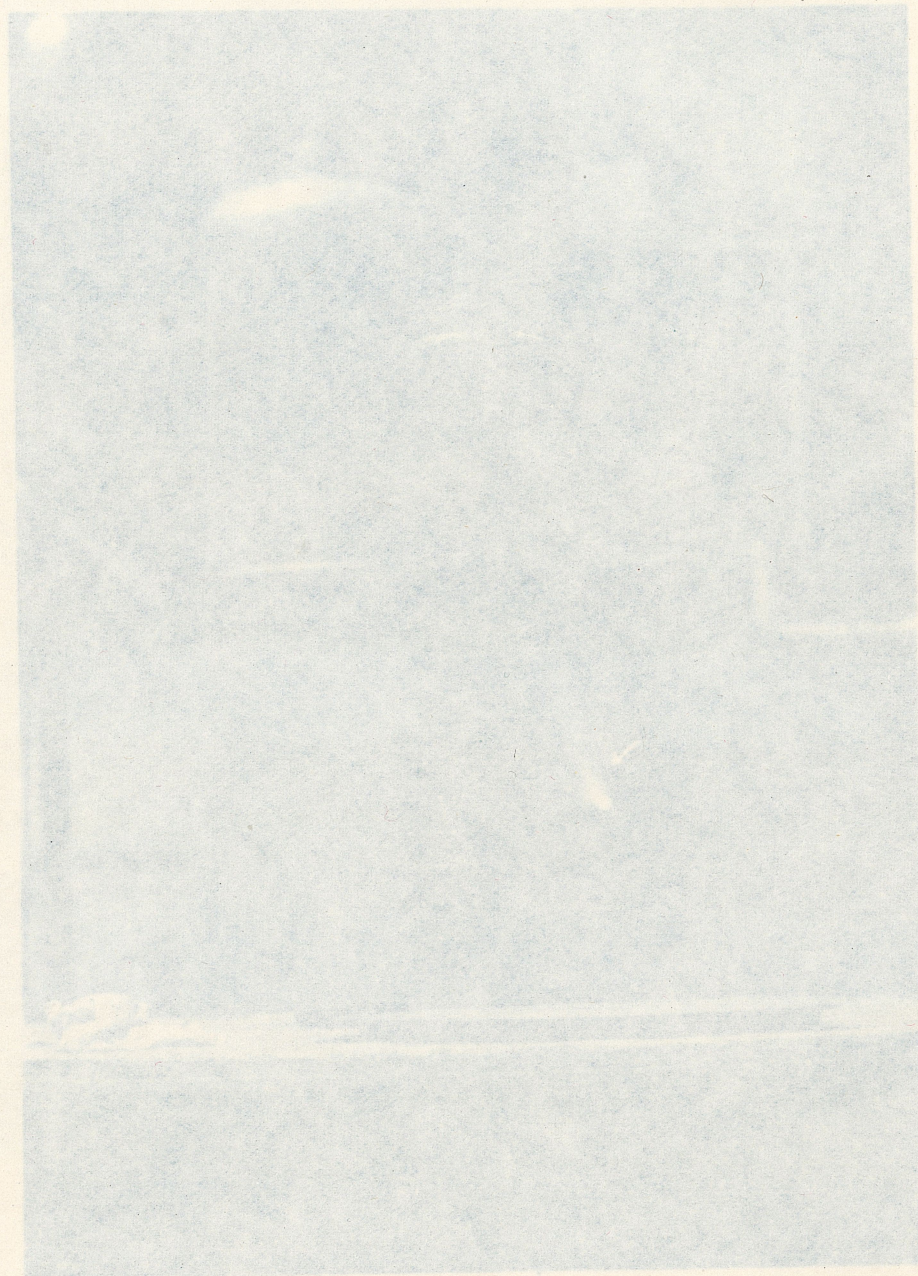


3365-17
138 KV TYPE F BUSHING
60 CYCLE VOLTAGE APPLIED
CORONA STREAMERS FROM BUSHING DOME AND GROUND ROD -
10 INCH ROD ON GROUND PLANE
PL-34728



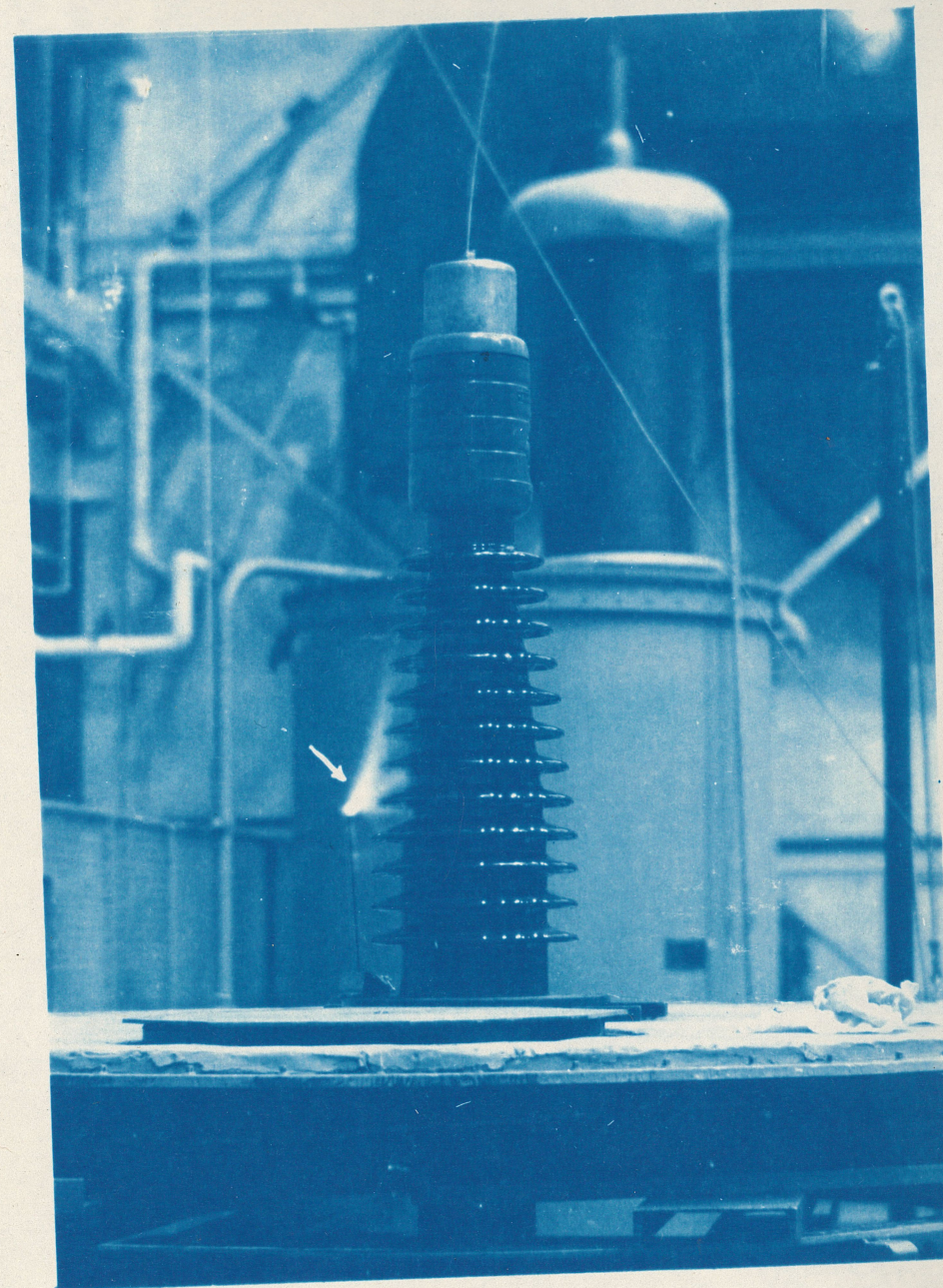
3365-17
138 KV TYPE F BUSHING
60 CYCLE VOLTAGE APPLIED
CORONA STREAMERS FROM LUG ON BUSHING DOME AND GROUND ROD -
16 INCH ROD ON GROUND PLANE

PL-34729



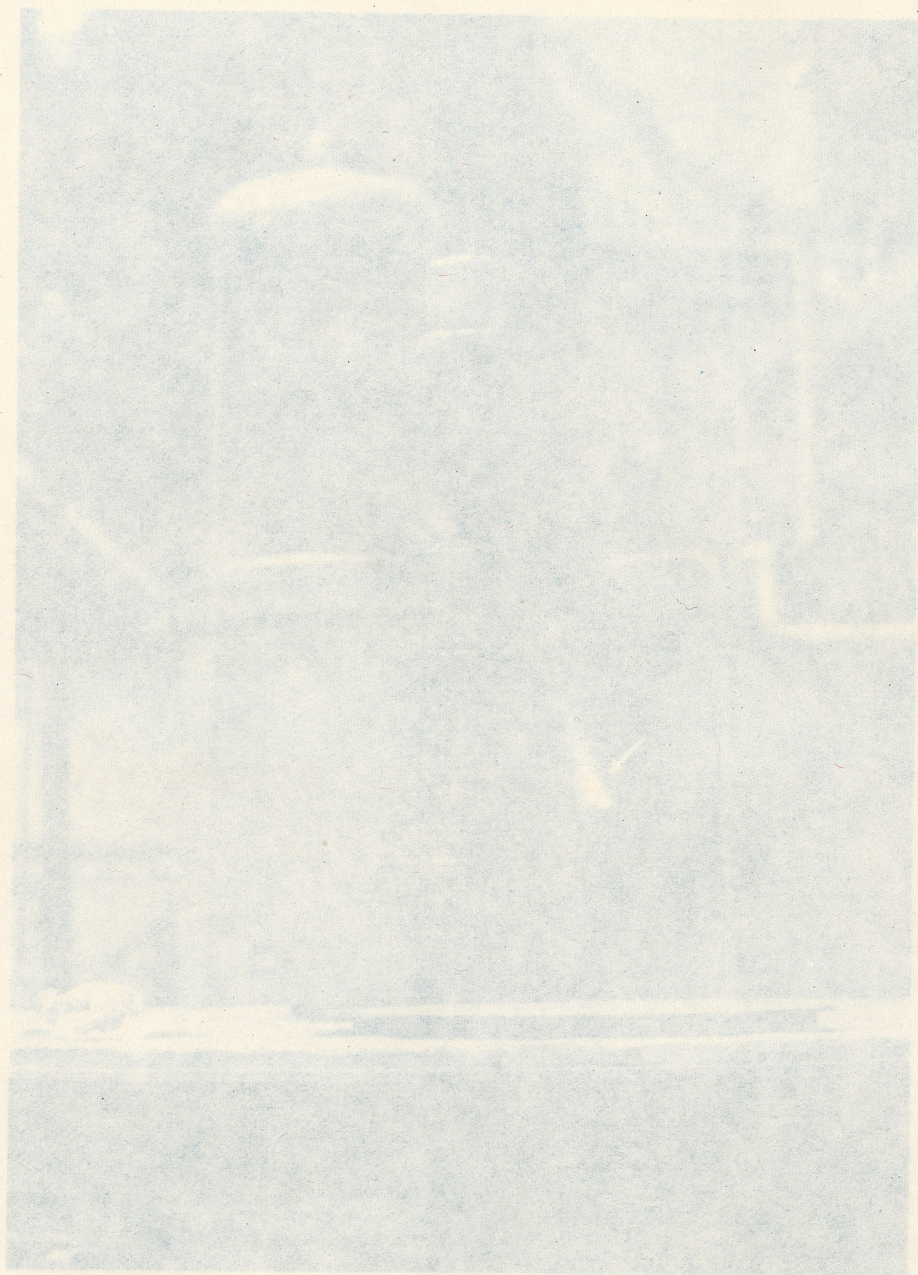
3365-15
138 KV TYPE F BUSHING
60 CYCLE VOLTAGE APPLIED
CORONA STREAMERS FROM TOP ON BUSHING DOME AND GROUND ROD -
16 INCH ROD ON GROUND PLANE

PL-34730



3365-15
138 KV TYPE F BUSHING
60 CYCLE VOLTAGE APPLIED
CORONA STREAMERS FROM GROUND ROD -
16 INCH ROD ON GROUND PLANE

PL-34730



51-5632

155 KV TYPE 1 BUSHING
60 CYCLE VOLTAGE APPLIED
CORONA STREAMERS FROM GROUND ROD -
1/8 INCH ROD ON GROUND PLANE

PL-34730